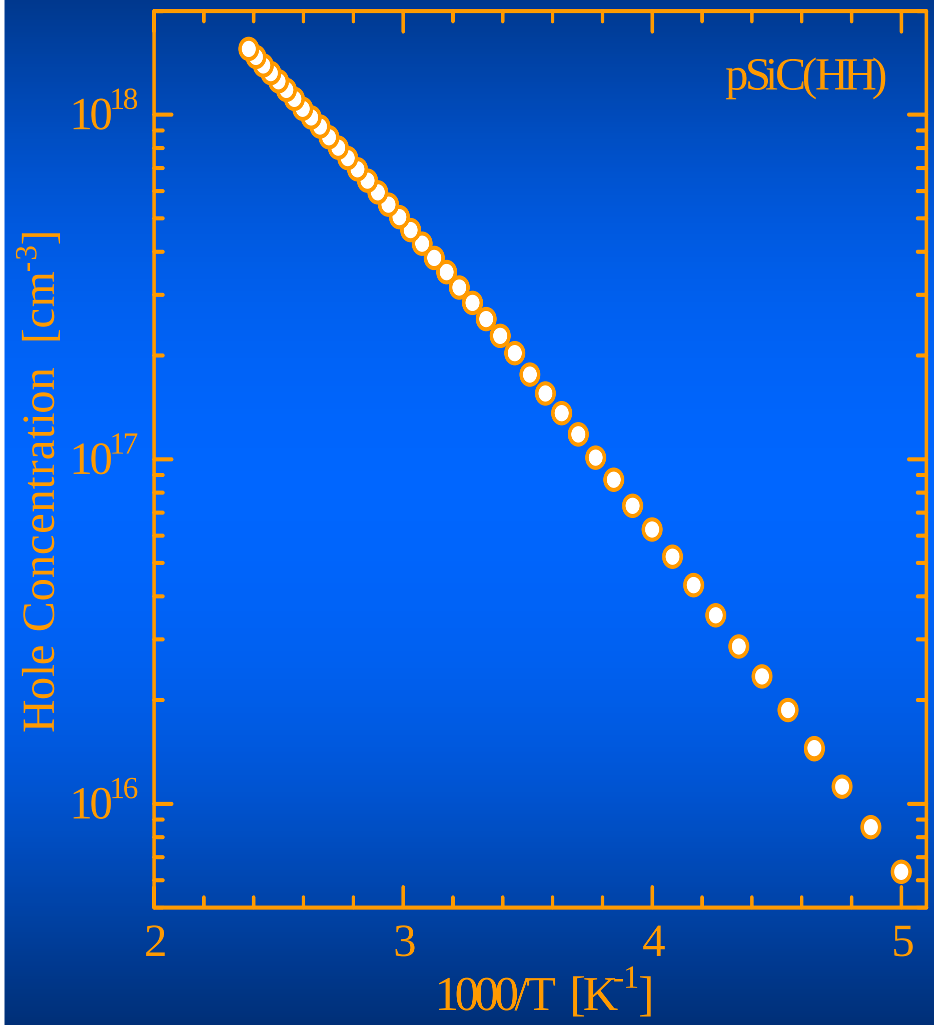
Real Relationship between Acceptor Density and Hole Concentration in Al-implanted 4H-SiC

H. Matsuura, K. Sugiyama, K. Nishikawa, T. Nagata and N. Fukunaga

Osaka Electro-Communication University
E-mail: matsuura@isc.osakac.ac.jp
Web site: http://www.osakac.ac.jp/labs/matsuura/

Acceptor density in Al-implanted 4H-SiC layer



1. Hall-Effect measurements

   Fermi-Dirac (FD) distribution function

$$f_{\mathrm{FD}}(\Delta E_{\mathrm{A}}) = \frac{1}{1 + 4\exp\left(\dfrac{\Delta E_{\mathrm{A}} - \Delta E_{\mathrm{F}}}{kT}\right)}$$

   Results determined by curve-fitting

$$N_{\mathrm{A}} = 4.85\times10^{19}\ \mathrm{cm}^{-3}$$
$$\Delta E_{\mathrm{A}} = 157\,\mathrm{meV}$$

2. TRIM

   Concentration of Al atoms in layer is ~$1\mathrm{x}10^{19}$ cm^{-3}

Is the FD distribution function available for Al acceptor in SiC?

Ground and excited states of Acceptor in SiC

Hydrogenic model

$$\Delta E_r = 13.6 \frac{m^*}{m_0 \varepsilon_s^2} \cdot \frac{1}{r^2} \ \ \text{eV}$$

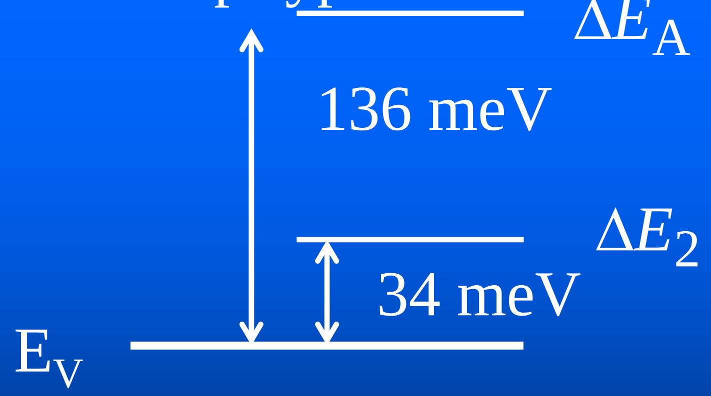
Acceptor Level (ground state level)

$$\Delta E_{\mathrm{A}} = \Delta E_1 = 136 \ \ \text{meV}$$

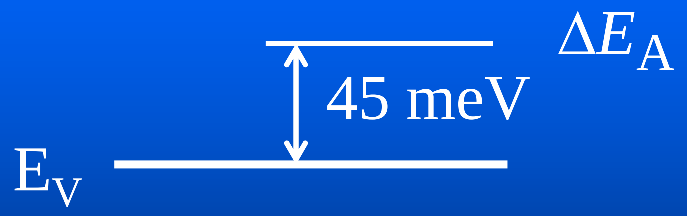
First excited state level

$$\Delta E_2 = 34 \ \ \text{meV}$$

In the case of p-type SiC



In the case of B-doped Si



It is necessary to consider a distribution function including the influence of the excited states!!

Conventional distribution function including the influence of excited states

$$f_{\mathrm{conv}}(\Delta E_{\mathrm{A}}) = \frac{1}{1+4\left\{\exp\left(\frac{\Delta E_{\mathrm{A}}-\Delta E_{\mathrm{F}}}{kT}\right)+\underbrace{\sum_{r=2} g_r \exp\left(\frac{\Delta E_r-\Delta E_{\mathrm{F}}}{kT}\right)}\right\}}$$

↓

Hardly any holes can be emitted into the valence band, because they are captured at the excited states.

↓

N_A higher than N_A obtained by the FD distribution function is required in order to meet p(T).

R. A. Smith, Semiconductors, 2nd ed. (Cambridge University Press, 1978) p. 92.

Proposed distribution function including the influence

$$f(\Delta E_A) = \frac{1}{1 + 4\exp\left(-\frac{\overline{E_{\mathrm{ex}}}}{kT}\right) \cdot \left\{\exp\left(\frac{\Delta E_{\mathrm{A}} - \Delta E_{\mathrm{F}}}{kT}\right) + \sum_{r=2} g_r \exp\left(\frac{\Delta E_r - \Delta E_{\mathrm{F}}}{kT}\right)\right\}}$$

↓

This term makes acceptors release holes at high temperatures more easily than $f_{\mathrm{conv}}(\Delta E_{\mathrm{A}})$.

Ensemble average of ground and excited state levels

$$\overline{E_{\mathrm{ex}}} = \frac{\sum_{r=2} (\Delta E_{\mathrm{A}} - \Delta E_r)\; g_r \exp\left(-\frac{\Delta E_{\mathrm{A}} - \Delta E_r}{kT}\right)}{g_1 + \sum_{r=2} g_r \exp\left(-\frac{\Delta E_{\mathrm{A}} - \Delta E_r}{kT}\right)}$$

Average acceptor level: $\overline{\Delta E_{\mathrm{A}}} = \Delta E_{\mathrm{A}} - \overline{E_{\mathrm{ex}}}$

H. Matsuura, New Journal of Physics, 4 (2002) 12.1 (http://www.njp.org/)

Is the real relationship between N_A and p(T) necessary to simulate electric characteristics of devices?

When band bending is calculated by Poisson equation:

$$\frac{d^2V(x)}{dx^2} = -\frac{q}{\varepsilon_s \varepsilon_0}\left(N_D^+ - N_A^- + p - n\right)$$

$$p = N_A\left[1 - F(\Delta E_A)\right]$$

$$N_A^- = N_A F(\Delta E_A)$$

Acceptor density N_A

Distribution function $F(\Delta E_A)$

Acceptor density much higher than the real density is required. ⇐ Using FD distribution function $f_{FD}(\Delta E_A)$

Using real acceptor density ⇒ What distribution function is suitable for acceptors?

Experimental

Implantation of Al atoms into 4H-SiC

Implantation energies: 1.0, 1.6, 3.3, 4.4, 5.6 and 7.0 MeV

Average N_A in a box profile: ~1×10^{19} cm^{-3}

Sample number	Implantation temp.	Annealing temp.
pSiC(HH)	1000 ºC	1575 ºC
pSiC(HL)	1000 ºC	1443 ºC
pSiC(LH)	Room temp.	1575 ºC
pSiC(LL)	Room temp.	1443 ºC

Hall-effect measurements

Temperatures: 200 K ~420 K

Magnetic field: 1.4 T

Free Carrier Concentration Spectroscopy(FCCS)

FCCS signal: $$H(T,E_{\mathrm{ref}}) \equiv \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right)$$

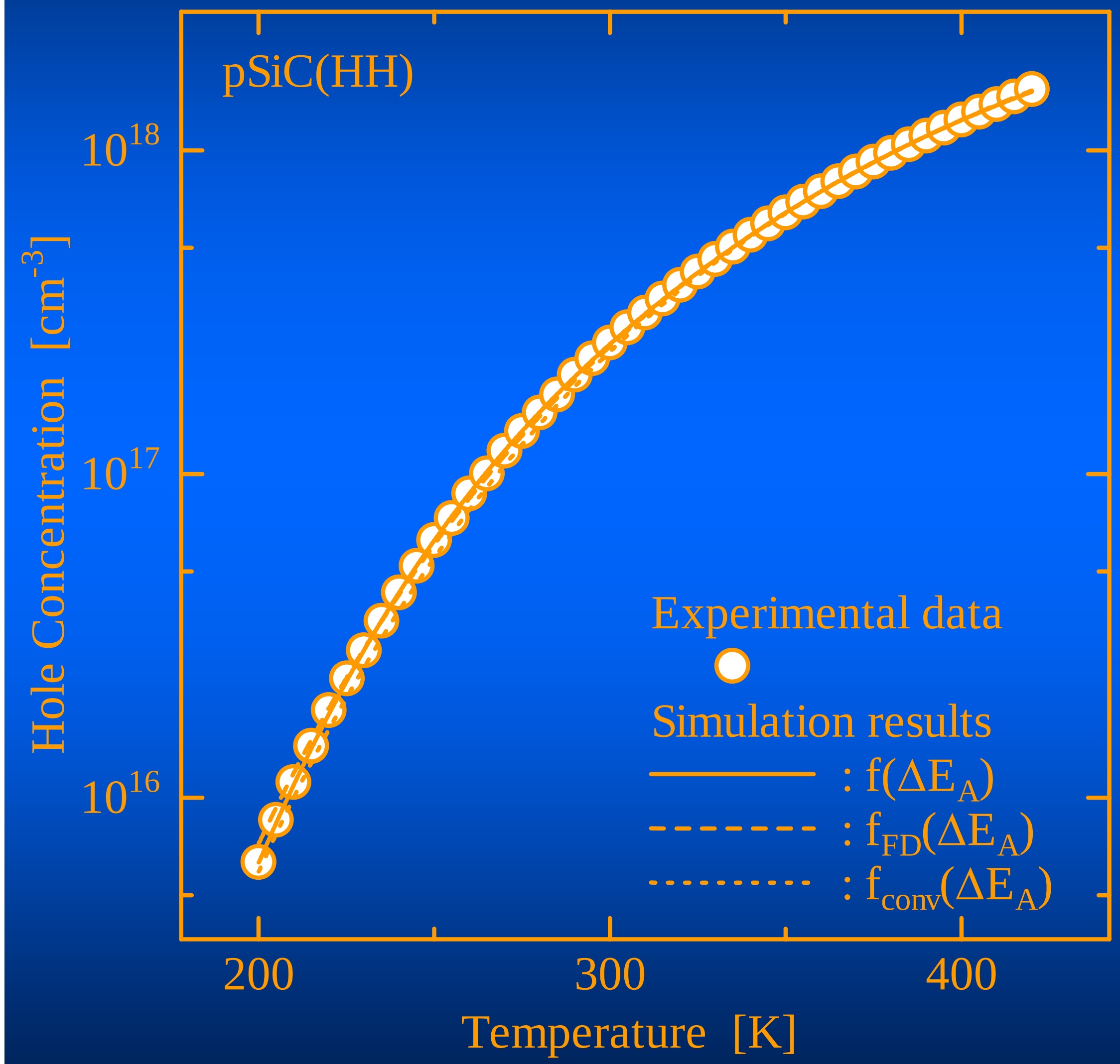
The FCCS signal has a peak at temperature corresponding to each acceptor. $$T_{\mathrm{peak}} \simeq \frac{\Delta E_{\mathrm{A}} - E_{\mathrm{ref}}}{k}$$ $$H(T_{\mathrm{peak}}, E_{\mathrm{ref}}) \simeq \frac{N_{\mathrm{A}}}{kT_{\mathrm{peak}}} \exp(-1)$$

Results obtained by FCCS in pSiC(HH)

$F(\Delta E_A)$	N_A [cm^{-3}]	ΔE_A [meV]	N_{comp} [cm^{-3}]
$f(\Delta E_A)$	1.21×10^{19}	177	2.29×10^{17}
$f_{FD}(\Delta E_A)$	4.85×10^{19}	157	2.45×10^{18}
$f_{conv}(\Delta E_A)$	4.69×10^{20}	167	1.62×10^{19}

Rather high N_A is required in $f_{FD}(\Delta E_A)$ or $f_{conv}(\Delta E_A)$.

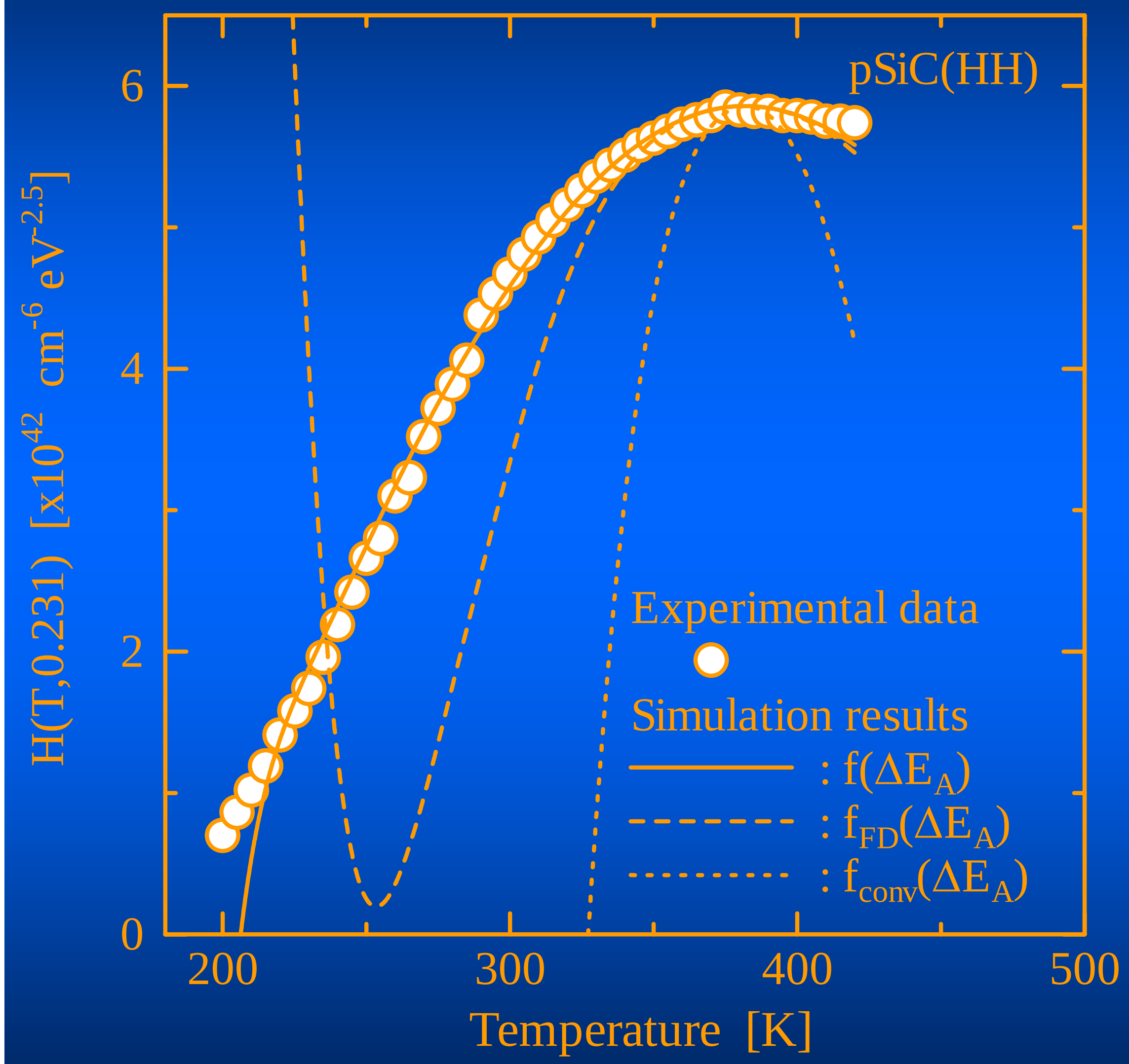
A set of three p(T) simulated using the obtained values



All the simulated p(T) are in good agreement with the experimental p(T).

The curve-fitting procedure of p(T) is not suitable for investigating the influence of the excited states on p(T).

A set of three simulated FCCS signals



All the peaks of the simulated FCCS signals coincide with the peak of the experimental FCCS signal.

However the solid curve is in better agreement with the experimental FCCS signal than the others.

FCCS is appropriate for investigating the influence of the excited states on p(T).

Obtained results for samples with different $T_{implant}$ and T_{anneal}

Sample number	N_A [cm^{-3}]	ΔE_A [meV]	N_{comp} [cm^{-3}]
pSiC(HH)	$1.21\text{x}10^{19}$	177	$2.29\text{x}10^{17}$
pSiC(HL)	$9.49\text{x}10^{18}$	187	$1.62\text{x}10^{17}$
pSiC(LH)	$7.14\text{x}10^{18}$	178	$6.64\text{x}10^{16}$
pSiC(LL)	$5.44\text{x}10^{18}$	183	$1.23\text{x}10^{17}$

Almost all implanted Al atoms in pSiC(HH) behave as an acceptor, while only a half of Al atoms in pSiC(LL) act as an acceptor.

$T_{implant}$ is effective in forming acceptors in SiC.

Summary

Al-implanted p-type 4H-SiC layers with different $T_{implant}$ and T_{anneal} were fabricated.
The p(T) in those layers were obtained from Hall-effect measurements.

In order to obtain the reliable acceptor density from p(T), a distribution function including the influence of the excited states of acceptors is found to be required.

In order to investigate the influence of the excited states, FCCS is considered to be more appropriate than the curve fitting procedure of p(T).

When $T_{implant}$=1000 ^{o}C and T_{anneal}=1575 ^{o}C, almost all implanted Al atoms are found to behave like an acceptor in SiC.